

Mini-review on Lepton Flavor and CP Violation in SUSY^a

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ABSTRACT

Lepton flavor and CP violation in supersymmetric models are briefly reviewed. After a short motivation and an introduction to the phenomenology, model independent constraints on mass insertions, predictions of SUSY GUT models and rates for several LFV and CPV processes are presented.

1. Motivation

In spite of the impressive success of the standard model (SM), there are two pieces of evidence for physics beyond, both related to the subject of this talk: lepton flavor violation (LFV), CP violation and supersymmetry (SUSY). The first, neutrino oscillations (neutral LFV), indicate non-zero neutrino masses and mixings (their size explained naturally by the seesaw mechanism). The second, the observed baryon asymmetry of the Universe, requires new sources of CP violation (leptogenesis could be induced by heavy Majorana neutrinos, and electroweak baryogenesis is possible in SUSY extensions of the SM).

Neutrino masses introduce negligible charged LFV effects (one loop, GIM suppressed) and negligible CPV effects (three loops) in the SM. In contrast, embedded in a SUSY framework the flavor structure that they suggest implies new sources of FV (misalignment between lepton and slepton mass matrices) and CP violation that show up to one loop and are GIM unsuppressed. In the seesaw mechanism SUSY would be necessary to cancel the large corrections to the Higgs mass proportional to the Majorana scale.

2. Phenomenology

In the minimal supersymmetric SM (MSSM) with R-parity and seesaw neutrino masses, the relevant parameters are the heavy Majorana neutrino masses, the complex parameter μ , charged lepton and neutrino Yukawa couplings (in the superpotential) and complex SUSY soft-breaking bilinear and trilinear terms (flavor-diagonal gaugino masses and flavor-nondiagonal, CP-violating slepton mass matrices). At the electroweak scale heavy neutrinos decouple and our observables are the SUSY masses and mixings (bounded by LFV decays and EDMs of charged leptons) and the light neutrino masses and mixings (partially measured in neutrino oscillation experiments). The neutrino Yukawa matrix \mathbf{Y}_ν , in the basis where the heavy-neutrino mass matrix \mathbf{M}_N is \mathbf{D}_M diagonal, can be obtained only up to a complex orthogonal matrix \mathbf{R} from the light-neutrino (symmetric)

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mass matrix \mathcal{M}_ν (diagonalized by $\mathbf{D}_m = \mathcal{U}^T \mathcal{M}_\nu \mathcal{U}$) [1]:

$$\mathcal{M}_\nu = v^2 \sin^2 \beta \mathbf{Y}_\nu^T \mathbf{M}_N^{-1} \mathbf{Y}_\nu \quad \Rightarrow \quad v \sin \beta \mathbf{Y}_\nu = \sqrt{\mathbf{D}_M} \mathbf{R} \sqrt{\mathbf{D}_m} \mathcal{U}^\dagger. \quad (1)$$

A redefinition of the fields and the symmetries of the Lagrangian lead to a few physical phases: one Dirac and two Majorana phases in the MNS matrix (\mathcal{U} in the basis where \mathbf{Y}_e is diagonal), the SUSY phase $\arg(\mu)$ (in chargino and neutralino mass matrices), the SUSY-breaking phase $\arg(A_0)$ (the trilinear coupling, taken universal at some scale, in the left-right mixing of the slepton mass matrix) and the three phases of \mathbf{R} .

The relevant interaction vertices of the mass eigenstates $\tilde{\nu}_X \tilde{\chi}_A^- \ell_I$ and $\tilde{\ell}_X \tilde{\chi}_A^0 \ell_I$ can be parametrized by $ig(c_{IAX}^L P_L + c_{IAX}^R P_R)$ where $P_{L(R)} = \frac{1}{2}(1 \mp \gamma_5)$ and the couplings $c_{IAX}^{L,R}$ involve chargino, neutralino, slepton and lepton mixings. At present the most stringent constraints on these couplings come from LFV decays $\ell_J \rightarrow \ell_I \gamma$, the muon ($g - 2$) and the electron EDM which are all (chirality-flipping) dipole transitions/momenta that can be parametrized by magnetic and electric dipole form factors. Charginos-sneutrinos and neutralinos-charged sleptons are exchanged in one-loop triangular diagrams. The form factors in terms of both generic couplings and SUSY parameters can be found in Ref. [2].

3. Model-independent constraints

The (6×6) charged slepton and (3×3) sneutrino mass matrices can be rewritten in terms of several types of mass insertions (flavor basis $\alpha, \beta = 1, 2, 3$) [3]:

$$(\delta_{LL}^{\tilde{\nu}})_{\alpha\beta} \equiv \frac{(M_{\tilde{\nu}}^2)_{\alpha\beta}}{\tilde{m}^2}, \quad (\delta_{LL}^{\tilde{\ell}})_{\alpha\beta} \equiv \frac{(m_{LL}^2)_{\alpha\beta}}{\tilde{m}^2}, \quad (\delta_{RR}^{\tilde{\ell}})_{\alpha\beta} \equiv \frac{(m_{RR}^2)_{\alpha\beta}}{\tilde{m}^2}, \quad (\delta_{LR}^{\tilde{\ell}})_{\alpha\beta} \equiv \frac{(m_{LR}^2)_{\alpha\beta}}{\tilde{m}^2}, \quad (2)$$

where \tilde{m} is an average slepton mass. This parametrization is (SUSY) model independent. The flavor non-diagonal mass insertions ($\alpha \neq \beta$) are constrained experimentally in LFV processes, assuming that only one type of deltas contribute to a given process, ignoring potential cancellations. Notice that δ_{LL} and δ_{RR} are hermitian, so that $\text{Im}(\delta_{LL,RR})_{\alpha\alpha} = 0$. This means that the only contribution from the chargino-sneutrino sector to the EDM comes from the SUSY phase $\arg(\mu)$.

The form factors are dominated by contributions proportional to $c_{IAX}^{L(R)*} c_{JAX}^{R(L)}$ (the chirality flip takes place in internal lines) and go like $m_{\ell_J} \tan \beta \delta_{LL}^{\tilde{\nu}}$, $m_{\ell_J} \tan \beta \delta_{LL,RR}^{\tilde{\ell}}$, $M_1 \delta_{LR}^{\tilde{\ell}}$. This means that bounds on $\delta_{LR}^{\tilde{\ell}}$ are essentially independent of $\tan \beta$ and stronger than the others, which in contrast are more restrictive for large $\tan \beta$. The δ_{LL} insertions receive both U(1) and SI(2) contributions. There are two dominant U(1) contributions for large $\tan \beta$ to $\delta_{LL(RR)}$ that have same (opposite) signs. The cancellations make δ_{RR} be less constrained than δ_{LL} [4]. The branching ratios roughly grow like $\delta_{LL,RR}^2 \tan^2 \beta$.

The present limit $\text{BR}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$ strongly constrains the LFV mass insertions between the first two families in the charged slepton sector, except for incidental cancellations of neutralino contributions, leading to $(\delta_{LL,RR}^{\tilde{\ell}})_{12} \lesssim 10^{-5}$ to 10^{-3} (stronger for higher $\tan \beta$) and $(\delta_{LR}^{\tilde{\ell}})_{12} \lesssim 10^{-6}$. Due to the large lepton mixing (neutrino oscillations) the same limit constrains all the sneutrino mass insertions $(\delta_{LL}^{\tilde{\nu}})_{12,13,23} \lesssim 10^{-5}$ to 10^{-3} .

Since $\text{BR}(\tau \rightarrow e\gamma, \mu\gamma) \lesssim 10^{-7}$, the LFV mass insertions involving the third family are little constrained. See for instance Refs. [5,6].

The present limit on the electron EDM $d_e \lesssim 10^{-27}$ ecm restricts the imaginary part of the flavor-diagonal insertion $(\delta_{LR}^{\ell})_{ee}$ (to the level of 10^{-8}) and $\arg(\mu)$ (less strongly due to a possible conspiracy of Majorana phases). From present limits on d_μ and d_τ there are no significant constraints. See Ref. [6].

4. Predictions for radiative lepton decays in SUSY GUT models

The experimental limits imply a very fine alignment of lepton and slepton mass matrices. This is generally formulated as the SUSY flavor problem: how to explain such an alignment when fermion and sfermion masses have a different origin, the former from Yukawa interactions and the latter from a soft SUSY-breaking mechanism.

Even if the SUSY-breaking mass matrix was diagonal and universal, as in SUGRA, at a high scale, the renormalization group (radiative) corrections down to the electroweak scale introduce off-diagonal entries due to non universal Yukawa interactions.

Assuming universality at the GUT scale M_X , there are corrections proportional to $(\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu)_{ij} \log(M_X/M)$ in the slepton left-handed sector. Since $Y_\nu \sim \sqrt{m_\nu M}/(v \sin \beta)$, LFV is enhanced for $M \sim 10^{14}$ GeV ($Y_\nu \sim 1$). The scenario with minimal LFV is that of quasidegenerate neutrinos and a real matrix \mathbf{R} (though incompatible with leptogenesis [7]). These corrections are then independent of \mathbf{R} . One can distinguish two cases compatible with the lepton mixings observed at low energy [2]: (a) high $\tan \beta$ ($Y_\tau \sim 1$) with CKM-like mixings at GUT scale (radiative magnification [8]) and (b) low $\tan \beta$ ($Y_\tau \ll 1$) where lepton mixing angles do not run. Assuming universality at the Planck scale M_P , in the simplest SU(5) grand unification model, there are also top-quark induced corrections proportional to $(\mathbf{Y}_\mathbf{u}^\dagger \mathbf{Y}_\mathbf{u})_{ij} \log(M_P/M_X)$ in the slepton right-handed sector. Present limits on $\mu \rightarrow e\gamma$ exclude case ‘a’ for large neutrino couplings, and the non observation in the future of $\mu \rightarrow e\gamma$ at PSI or $\tau \rightarrow \mu\gamma$ at KEK would exclude the magnification model [2].

Quarks and leptons share multiplets in GUT models, leading to a correlation between leptonic and hadronic FCNC and CP [9]. In SU(5), $\text{BR}(\tau \rightarrow \mu\gamma)$ restricts the SUSY contribution to $A_{CP}(B \rightarrow \phi K_S)$ and limits on $(\delta_{RR}^d)_{12(13)} \leftrightarrow (\delta_{LL}^{\ell})_{12(13)}$ from Δm_K and $B_0 - \bar{B}_0$ compete with those from $\text{BR}(\mu \rightarrow e\gamma)$ and $\text{BR}(\tau \rightarrow e\gamma)$, respectively. In SO(10), limits on $\text{BR}(\ell_J \rightarrow \ell_I \gamma)$ complement SUSY direct searches at LHC, and $\tau \rightarrow \mu\gamma$ is more restrictive than $b \rightarrow s\gamma$.

5. Other LFV processes

$\ell_J \rightarrow 3\ell_I$: The contribution of photon-exchange penguins to the branching ratio is $\mathcal{O}(\alpha)$ smaller than the $\text{BR}(\ell_J \rightarrow \ell_I \gamma)$ (Z -penguins and box diagrams are subdominant) and that of Higgs-penguins grow with $\tan^6 \beta/M_A^2$ [10]. In particular, limits from $\text{BR}(\tau \rightarrow 3\mu)$ compete with those from $\text{BR}(\tau \rightarrow \mu\gamma)$ for light Higgs masses and large $\tan \beta$.

$\mu \rightarrow e$ conversion in nuclei: The contribution of photon-penguins to the conversion rate is $\sim 6 \times 10^{-3}$ smaller than the $\text{BR}(\mu \rightarrow e\gamma)$, but Higgs-penguin contributions $\propto \tan^6 \beta/M_A^2$

may dominate [11], making forthcoming data from $\mu N \rightarrow eN$ competitive with $\mu \rightarrow e\gamma$.

LFV Higgs decays: A $\text{BR}(h, H, A \rightarrow \tau\mu) \sim 10^{-4}$ for large $\tan\beta$ and $M_{\text{SUSY}} \lesssim 1 \text{ TeV}$ (at reach of LHC for $M_A \lesssim 300 \text{ GeV}$) is compatible with limits on $\text{BR}(\tau \rightarrow \mu\gamma)$ [12].

LFV Z decays: The $\text{BR}(Z \rightarrow \ell_I \ell_J)$ (dominantly chirality-preserving) are related but not proportional to the $\text{BR}(\ell_J \rightarrow \ell_I \gamma)$. $\text{BR}(Z \rightarrow \tau\mu, \tau e) \lesssim 10^{-8}$ (at reach of GigaZ) compatible with present limits on $\text{BR}(\tau \rightarrow \mu\gamma, e\gamma)$ are achievable for low $\tan\beta$ [5,13].

Collider tests: At the LC the main signal is production and decay of sleptons, charginos and neutralinos. For different mSUGRA benchmark points $\sigma(e^+e^- \rightarrow \tau^+\mu^- + 2\tilde{\chi}_1^0) = 0.05 - 10 \text{ fb}$ at $\sqrt{s} = 800 \text{ GeV}$ are possible and compatible with $\text{BR}(\tau \rightarrow \mu\gamma) \lesssim 10^{-8}$ (foreseen at the LHC) [14].

6. Conclusions

SUSY GUT models predict a misalignment of lepton and slepton mass matrices even if one assumes a flavor-blind SUSY breaking mechanism (mSUGRA, GMSB, AMSB), and correlate leptonic and hadronic FCNC and CP. LFV and CPV in these models should be observed in upcoming experiments.

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